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HIGH RESOLUTION SONAR CONCEPT FORMULATION

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An assessment is made of the impact of current technological developments on future research in high resolution sonar. The philosophical approach is from the point of view of examining the rate of information flow at each stage through the system. It is concluded that large computer memories under microprocessor control and fiber optic data links can be fruitfully applied in future system architecture. In addition, the necessity for further research in precision navigation systems and pattern recognition algorithms

#20--became apparent, in order to achieve reliable classification of underwater objects along with high area search rates.

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HIGH RESOLUTION SONAR CONCEPT FORMULATION

I. INTRODUCTION

This report is a summary of work done at Naval Coastal Systems Center during July and August 1979 in attempting to assess the impact of current technological developments on future research in high resolution sonar. Rather than an exhaustive survey of relevant technologies, a few were selected as being of the highest probability for significant improvements in target classification capability along with greater area search sweep rate. The philosophical approach is from the point of view of examining the rate of information flow through the system at each stage. Technologies were evaluated on this basis and it was concluded that three are dominant--large computer memories, microprocessor control, and fiber optic data links.

A side-looking sonar example is used to illustrate how these technologies might be incorporated into a future system. Many of the concepts considered in this report have already been incorporated in developmental or proposed systems at NCSL and elsewhere. This is to be expected and should simply be a confirmation that the limitations of physics will often lead research to similar trends while advances in technology determine the rate of progress.

II. SYSTEM EXAMPLE: SIDE-LOOKING SONAR

A. RESOLUTION AND SEARCH RATE REQUIREMENTS

The geometry of a side-looking sonar is constrained by the linear aperture oriented along the track of the support platform. Along-track-resolution is related to effective aperture size, while range resolution is related to signal bandwidth. Therefore both aperture and bandwidth must be maximized within the physical constraints to achieve the highest possible resolution. Practical limitations on physical aperture size provide motivation for synthetic aperture development, and the search for bandwidth leads to development of new signal waveforms and wideband transducers. Meanwhile, tactical considerations motivate efforts to increase area search rate, which implies increasing the sonar range capability in spite of the limits imposed by the velocity of propagation of sound. A variety of clever schemes (Ref. 1,2) have been proposed to meet these goals generally by application of parallel processing in time, space, and frequency.

If we assume that somehow larger apertures will be synthesized, wider bandwidth signals will be accomodated, and parallel processing will be employed, the rate of information flow into the system will be phenomenal. Even with the resolution and search rates already obtainable, the rate of information flow is so high that the system capacity is being overloaded at every stage, from the preamplifiers to the operator.

In order to quantify the problem as to relative magnitude, consider a side-looking sonar with constant resolution cell size at all ranges of 10 x 10 cm. This cell size is representative of the linear resolution required for reliable classification (on the order of 1/10 of the object size), as reported in several studies (Ref. 3). Synthetic aperture techniques inherently provide constant resolution cell size because the effective aperture length is proportional to range. Time variable focus of a physical aperture can also approach constant resolution.

If an area coverage rate of one square nautical mile per hour is taken as a benchmark which should be equaled or exceeded, the total number of resolution cells covered per second is approximately

$$\frac{2 \text{ km} \times 2 \text{ km} \times 100 \text{ cells/m}^2}{3600 \text{ sec/hr}} \approx 10^5 \text{ cells/second}$$

B. INPUT INFORMATION RATE

If the reflected power from each cell can be distinguished to eight "shades of grey", (or equivalently the signal/reverberation ratio is 9 dB), then each cell represents approximately three "bits" of information.[1] The information rate R_b at this point in the system is therefore on the order of 3×10^5 bits/sec.

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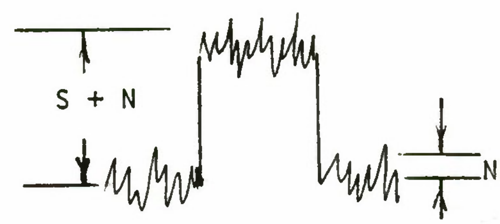
[1] Information can be measured quantitatively in terms of $\log_2$ of the number of distinguishable states of the data, represented by a binary number. The size of the binary number required measured in binary digits ("bits") gives the information content of the data. See Goldman (Ref. 4)

Another way of looking at the input information rate is to consider a linear aperture of length L. If the system bandwidth is W(Hz), independent samples of the signal can be measured approximately every 1/W seconds, or equivalently every c/W meters in space (where c = sound velocity). Therefore the aperture can gather LW/c independent samples of the wavefront at any instant of time. The number of distinguishable states is approximately $\frac{S + N}{N}$, hence the information rate is

$$R_a = \frac{L\,W^2}{c} \log_2 (1 + S/N)$$



Note that the information rate varies linearly with the aperture length, but only as the logarithm of the S/N ratio, while it is proportional to the square of the bandwidth.

Furthermore, the input information rate to the aperture R_a will be greater than the rate computed above for the beamformer output, R_b. Even though an ideal beamformer neither creates nor destroys information (in the simplest case it can be considered as performing a linear Fourier Transform on the aperture data) in practice there is certain to be some loss of information in the beamforming process. Therefore, the rate at the aperture will be even greater than at the beamformer output where resolution cells contain the information.

C. OUTPUT INFORMATION RATE

At the other extreme, an operator can make only a very modest number of reliable classification decisions per unit time. As a guess, the maximum number might be on the order of one decision per minute, each of which represents a classification between a small number of object categories. Allowing for 16 categories, an information rate for classification R_c is

$$R_c = \frac{\log_2 16}{60 \text{ sec/min}} = 1/15 \text{ bit/sec}$$

Therefore, an information rate compression of $15 \times 3 \times 10^5 = 4.5 \times 10^6$ must take place in the system.

III. INFORMATION RATE COMPRESSION

Information rate compression by definition implies some sort of memory or storage, since the input rate greatly exceeds the output rate and information must be "digested" somewhere. Many bits must be integrated together to come up with patterns which can be classified.

In a typical present day system, the compression occurs primarily in the eye and brain of the operator, since the information rate on the display is virtually of the same order of magnitude as the rate at the aperture. Essentially raw data is delivered in great quantity to the operator, who must bear the entire burden of sorting, rejecting, selecting and classifying it. There is a fundamental theorem of information theory by Shannon (Ref. 5) that each system has a certain "channel capacity" or maximum information rate measured in equivalent bits/second. The theorem states that if the actual data rate is significantly less than the channel capacity, the output decision error rate can be reduced arbitrarily by proper processing. Conversely, if the data rate exceeds the channel capacity, the probability of decision error increases toward unity very rapidly. Even though this theorem was derived for very precisely defined conditions, the basic idea most certainly applies in general, including to human operators. Therefore it should be clear that some sort of information rate compression is absolutely necessary in a high/resolution sonar system, which in turn implies the need for a large memory.

IV. INFORMATION TRANSMISSION

Since the information rate at the aperture is on the order of 10^6 bits/sec., there is a question of architecture as to how this processing of data will be distributed throughout the system. Locating the memory and its attendant support in an underwater body where space is at a premium does not seem desirable. On the other hand, if the memory is located remotely from the aperture, there is a corresponding need for high data rate transmission between aperture and memory. It is conceivable, for example, to connect the preamplifiers directly to A/D converters and transmit the transducer data from the aperture (which must be at some depth in the water) to the beamformers which could be aboard a surface platform. In fact such a scheme has been used in low frequency passive towed arrays where the data rate is very low compared to high resolution sonar. However, at the present stage of technology it appears to be more feasible to do the beamforming in the vicinity of the aperture. The higher frequencies associated with high resolution sonar discourage direct A/D conversion, even though the system bandwidth may be an order of magnitude less than the carrier frequency. The short wavelength of the high carrier frequency typically used is required to achieve the desired angular resolution, essentially by coherently processing the phase information in the wavefronts. Another approach has been proposed (ref. 2, op.cit.) using wideband signals to obtain bearing information from doppler time compression, using a lower frequency.

Even after beamforming, however, the information rate is quite high as discussed in the example of the side-looking sonar. However, at this point it becomes worthwhile to consider transmitting the data from the underwater body to a topside processor. The primary motivation for this is to reduce the size and expense of the underwater portion of the system since reduced size facilitates handling, and reduced expense makes loss or damage to the most vulnerable portion of the system less costly. It might eventually be possible to make the underwater portion of the system semi-expendable, with recovery being an option in its employment.

A fiber optic wideband link between the underwater body and the topside processor would be a promising application of new technology to high resolution sonar. Fiber optics offers the potential of low cost, low loss, and redundant and/or parallel data transmission in a very small diameter cable (Ref. 6). It is even possible to consider spooling the cable at both ends as is done with XBT wire and expending it along with the underwater portion of the system, rather than dragging it through the water.

V. INFORMATION STORAGE

At a rate on the order of 10^6 bits/sec., it is obvious that some buffering will be required at both ends of the data link. Some pre-processing could also be done before transmitting the data up the link. However, it looks more attractive to the author to concentrate most of the processing topside. Development of the system and later modifications to processing based on operation would be easier to incorporate, and size and weight and cost of the underwater body could be minimized.

Assuming that 10^6 bits/sec. is flowing into the memory, some preliminary arithmetic and logic operations could be performed by microprocessor devices to begin thresholding and batching the data for the first steps in rate compression. At this stage, most of the reverberation could be eliminated, and only portions of the field of view containing clusters of target-like features would be retained. It seems necessary that multiple looks at candidate clusters in both time and aspect angle will be required by any conceivable system to provide enough clues for classification (Ref. 7). For this reason, regions of memory should probably be organized on the basis of addresses being assigned to specific regions of physical space in the field of view, so that as more data about each region is accumulated it would be associated with previous data on the same region. This memory organization has been found to be essential in medical ultrasonics in order to provide image quality necessary for diagnosis, etc. In medical systems, the aperture location data is obtained mechanically from encoders connected to the linkage supporting the scanning transducer (Ref. 8). This requirement is closely related to the navigational data necessary for forming a synthetic aperture, hence any methods applicable to one problem apply more or less directly to the other. That is, the essential requirement is to know exactly where the aperture is located with respect to inertial space. This requirement appears to the author as the most crucial problem to be solved in order to achieve significant improvement in high resolution sonar. The requirements on technology are analyzed in a recent technical report by Griffith, et al. from The Analytical Sciences Corp. (Ref. 9). In order to reconstruct the image field, the aperture field must be known precisely over long distances.

It seems that some fundamental research concentrated on improving navigational resolution for this application is called for as soon as possible. Inertial systems, acoustic doppler correction techniques and/or other alternatives such as laser doppler velocimeters (Ref. 10) might be pursued as candidate systems.

VI. PATTERN CLASSIFICATION

It should be recognized at the outset that only a limited number of categories of object can be classified in the available time in typical search scenarios. Therefore, the objective of the data analysis is to extract sufficient clues for classification as rapidly as possible. These clues will be in the form of measurable parameters, such as relative level of energy reflection from each resolvable element in a candidate cluster. The reflected energy will be dependent upon aspect angle and coherent interference phenomena (speckle, scintillation, glint) which must be processed by suitable techniques. With sufficient computer capability, statistical measures of the image features can be formed, calculating the relative probability of occurrence of echoes of each strength. Use of this data to generate a suitable amplitude transfer function before thresholding provides a maximum contrast image of the field of view, enhancing image features (Ref. 11). For example, maximum and minimum values occuring in patterns such as highlights and shadows can be compared to time averages and spatial averages. Only clusters meeting certain criteria would be validated for display, in order to avoid overloading the operator.

Interactive graphics with the operator in the loop is desirable to keep the data flow to the operator at a rate which he can process. A family of patterns, any one of which could be classified as the same object, could be stored in ROM in microprocessors. Clusters falling into any of these patterns could be presented to the operator in an alphanumeric or symbolic code. Only after the operator selects a particular symbol with a cursor would the entire cluster be presented to him for examination. It is not proposed that automatic classification would do the whole job. There is too much potential variety of patterns in high resolution sonar for an automatic classifier to deal with them all. However, it is also impossible for an operator to examine the entire field of view and do all the pattern classification by himself. Therefore, a large computer memory is required to store the data, and a large number of microprocessor operations are required to accomplish the sorting and thresholding.

Fortunately, technology is advancing rapidly in this direction, as evidenced by electronic TV games and home computers which incorporate ROM's and interactive graphics. However, measures of "goodness" for pattern recognition cannot be obtained very consistently using human operators, because of difficulty in modeling the psychophysical phenomenon of perception (Ref. 12). Statistics gathered by testing humans is typically very unsatisfactory, with laboratory results not transferring well to operating conditions. On the other hand, the application of automatic pattern recognition theory to typical high resolution sonar images will require considerable effort to bring it to practical application. Multiple aspect data must be integrated in some fashion because the data at a single look and single aspect is insufficient to support the number of object classification categories that will be required. The need here does not seem to be for hardware technology as much as for software (algorithms) validated by application to a realistic data base.

VII. CONCLUSIONS

This analysis has shown that technological developments in computer memory, microprocessor control, and fiber optic transmission of large amounts of information can be fruitfully applied to high resolution sonar system architecture as sketched in Figure 1. However, in the course of this study, the key role of technology in high precision navigation systems became apparent. In order to accumulate sufficient information about underwater objects to achieve reliable classification, aperture data must be processed in multiple beams with variable focus, as sketched in Figure 2. It is essential that the spatial relationship of the aperture to an inertial reference be maintained precisely. Presently available inertial systems probably fall short of the requirement since they are designed for other applications. Update corrections by acoustic doppler or perhaps other means such as optical doppler using a rangegated or dual-beam laser might be considered for this problem (if the underwater platform is operated close enough to the bottom to allow the laser to overcome the optical attenuation of the water). In any case, the status of technology is unevenly developed in its readiness for application to high resolution sonar. Memories and microprocessors are here today, and fiber optics tomorrow, but high resolution navigation lags behind and seems to be a necessity to capitalize on the other developments.

Pattern recognition algorithms also must be developed in order to be applied to high resolution sonar images. Data and techniques from radar and optics may not be directly applicable because of differences in background and object characteristics. Very few resolvable elements or classification clues are available for typical objects of interest, so that the scene must be analyzed for several time intervals and several aspect angles to increase the number of clues. This returns the issue to the precision navigation system, which appears to be the most severe problem to be overcome in order to achieve the stated goals.

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EXAMPLE: SYSTEM ARCHITECTURE

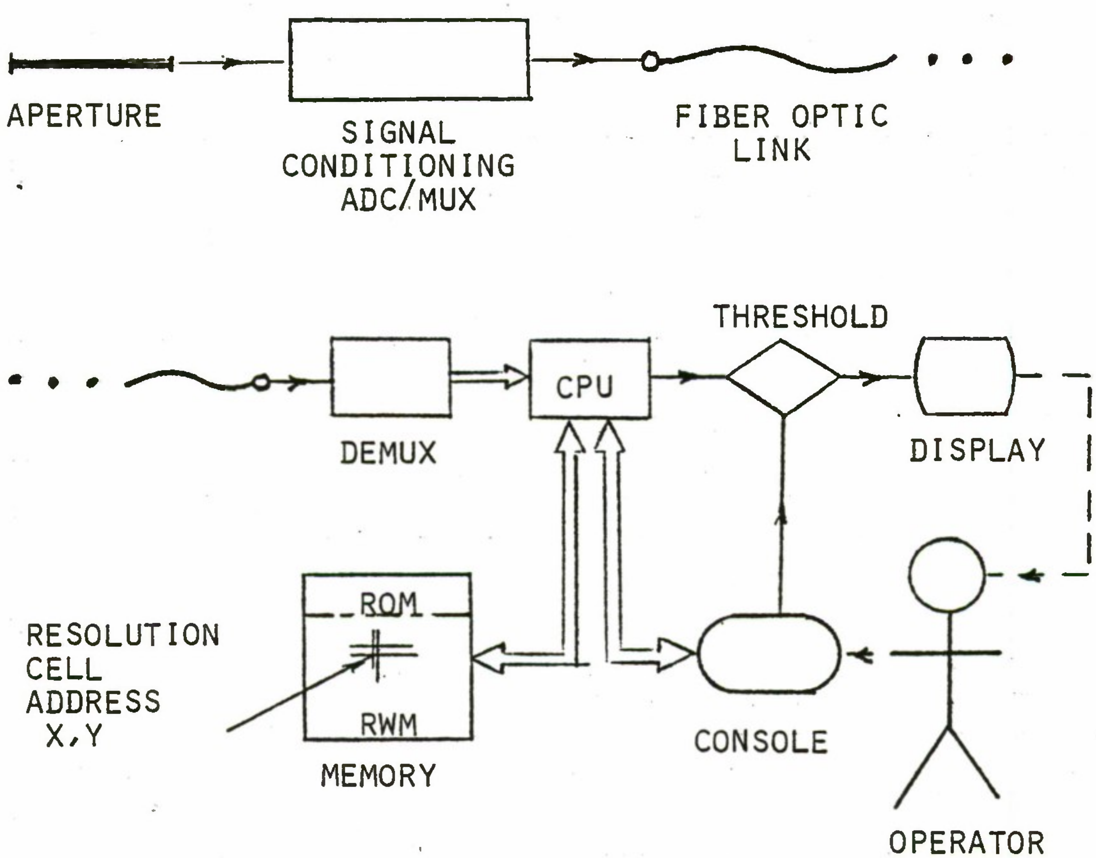
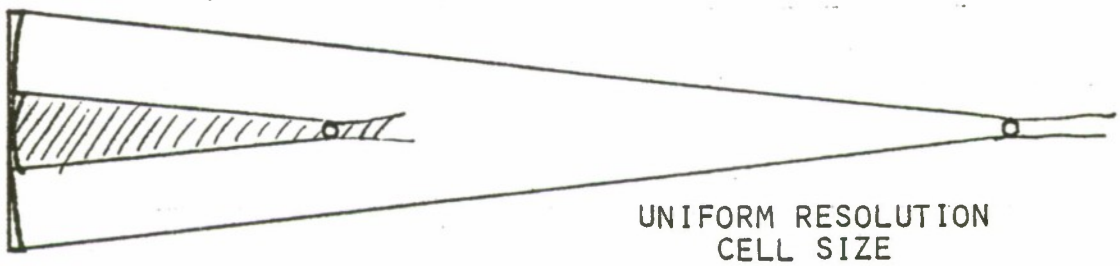
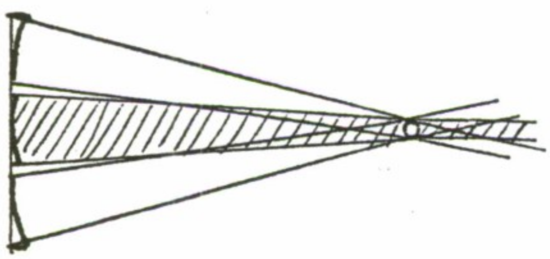


FIGURE 1--A computer memory is shown combined with a fiber optic data link to the aperture and interactive graphics output to the operator. The memory is organized on the basis of coordinates x,y in inertial space.

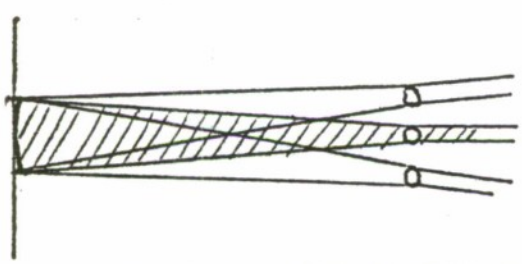
EXAMPLE: SHADOWGRAPH OR SYNTHETIC APERTURE



VARIABLE FOCUS, VARIABLE SIZE APERTURE



SUB-APERTURES, MULTIPLE ASPECT



MULTIPLE PRE-FORMED BEAMS

FIGURE 2--The aperture is shown maintaining constant resolution by size and focus with range (echo return time). Additional target classification information is obtained by multiple aspect, multiple echo beamforming.

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